Evaluation of Link Quality Estimators for Industrial Wireless Sensor Networks

Ruan D. Gomes, Marcelo S. Alencar, Diego V. Queiroz, and Iguatemi E. Fonseca

***Abstract*— In an industrial Wireless Sensor Network (WSN) the nodes are placed in harsh environments, so it is necessary to deal with problems related to fading and shadowing. In addition, the wireless channel in many industrial environments is non-stationary, and abrupt changes in long term channel characteristics can be observed. Thus, it is necessary to implement mechanisms and protocols to improve the quality of service. The Link Quality Estimators (LQE) are important building blocks for many protocols and mechanisms that use information about the links to improve the WSN performance. This paper evaluates some state-of-the-art LQEs for industrial WSN using a realistic simulation model.**

***Keywords*— Industrial wireless sensor networks, Link quality estimation, simulation.**

I. INTRODUCTION

To mitigate the low reliability of Wireless Sensor Networks (WSN) in industrial environments, it is necessary to deal with the problems that affect the wireless channel, such as shadowing and multipath fading [1]. Many industrial environments also present characteristics that make the wireless channel non-stationary, for long time periods, which can cause abrupt changes in the characteristics of the channel over time [2].

It is possible to deal with these problems using protocols that allow the network to self-adapt to the variations that occur in the Link Quality (LQ) over time. Some works focus on adaptive routing, in which the nodes can change the route if its quality becomes poor, such as the Collection Tree Protocol (CTP) [3]. Other works focus on dynamic channel allocation, in which the WSN nodes change the channel when it presents low quality [4]. The IEEE 802.15.4 standard, which is the usual communication standard for WSN, defines sixteen channels in the 2.4 GHz band. Due to the multipath profile of reflective industrial environments, the coherence bandwidth can be small, so that the characteristics of the communication medium can be different, even for adjacent channels [5].

In both cases, a mechanism is necessary to provide information about the LQ to the network nodes. The Link Quality Estimators (LQE) are fundamental building blocks in the development of adaptive routing protocols, and dynamic channel allocation mechanisms.

Baccour et al. [6] performed a comparative simulation study of LQEs for WSN, in which the statistical characteristics of some LQEs were evaluated, as well as their impact on the CTP protocol. In [7] the statistical properties of LQEs were analyzed for smart grid environments. The first one did not consider industrial environments, so the channel model used was not realistic for this type of environment. Although the study described in [7] had considered environments with characteristics compatible with industrial environments, only realistic parameters for the large-scale path loss, and shadowing were considered in the simulations. The non-stationary characteristics of the wireless channel in industrial environments were not considered, and only the results from the simulations considering an outdoor environment were described.

In this paper, the following state-of-the-art LQEs were evaluated: ETX [8], Four-Bit [9], F-LQE [10], and Opt-FLQE [7]. A realistic channel model for industrial WSN was used, which captures the effects of fading, shadowing, and the non-stationary characteristics of the channel in industrial environments. Using this model, which was first described in [11], it was possible to observe the accuracy and the reactivity of these LQEs, considering the non-stationary behavior of the wireless channel in industrial environments.

II. LINK QUALITY ESTIMATION

Some LQEs are based on physical layer information (hardware-based estimators), such as the Link Quality Indication (LQI) and the Received Signal Strength Indication (RSSI), and others are based on network or application layer information (software-based estimators), such as the Packet Reception Rate (PRR) and the Required Number of Packet Transmissions (RNP) [12].

The hardware-based estimators do not demand computational resources from the nodes, since the metric values are provided by the transceiver. Software-based estimators may require the transmission of diagnostic packets or conduct extra processing to estimate the Link Quality (LQ). However, using only the information provided by hardware-based estimators may not be sufficient.

The use of metrics based on PRR allows a good estimation for links with a very high quality or with a very low quality, but presents some problems in intermediate links. If the measurement window is small the estimation will present high reactivity, but very low stability, due to the high variation on the intermediate links. The WMEWMA estimator [12] uses a filter to achieve more stability to PRR. When retransmission is used, the metrics based on PRR can overestimate the LQ, since they do not consider the number of transmission attempts before a successful reception.

The metrics based on RNP estimate the required number of packet transmissions until a successful reception. A simple sender-side RNP estimator can underestimate the LQ due to the asymmetry, since it usually is based on ACK packets, and do not consider the actual PRR on the receiver.

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In this paper, four representative state-of-the-art LQEs were evaluated, that is: ETX, Four-Bit, F-LQE, and Opt-FLQE. These four LQEs consider link asymmetry in the estimation, which is very important for networks that use retransmissions. The F-LQE, and the Opt-FLQE takes into account four aspects of the link to get a holistic characterization of the LQ.

For industrial WSN the LQEs need to estimate the LQ with accuracy, and provide good stability, even with the small and rapid variations in the LQ due to the multipath fading. On the other hand, the estimator needs to rapidly identify abrupt changes in the channel characteristics. This research evaluated if these LQEs present good accuracy, stability, and reactivity for industrial environments. In the next subsections, the implementation details of each LQE are presented.

A. Expected Transmission Count (ETX)

The ETX [8] is a RNP-based, and receiver-initiated estimator, which considers link asymmetry by estimating the PRR in both directions, according to

$$e(w) = \frac{1}{p_d \times p_u}, \tag{1}$$

in which $e(w)$ is the value of ETX calculated using a set of w received packets in each direction; p_d is the PRR of the down link (from receiver to transmitter), and p_u is the PRR of the up link.

Probe broadcast packets are used to calculate the PRR in each node. One disadvantage of this approach is that it causes overhead in all nodes of the network to compute the values of the metrics and also generate extra traffic. As in [6], in the simulations peformed for this research a window $w = 5$ was used.

B. Four-Bit (FB)

The FB implements a hybrid active/passive, and sender-initiated estimator [9]. The LQ is determined using data packets and probe broadcast packets, that are combined to compute an estimative of the ETX. The value of ETX calculated using broadcast packets (e_b), is computed using $e_b = \frac{1}{p_f(w_b,\alpha)}$, in which $p_f(w_b,\alpha)$ is an estimation of the PRR, using an Exponentially Weighted Moving Average (EWMA) filter with history control factor α, and using a window with w_b received probe packets.

The value of ETX calculated using data packets (e_d) is computed using $e_d = \frac{w_d}{a}$, in which a is the number of ACK packets received for each w_d transmitted data packets. If a is equal to zero, e_d is equal to the number of transmissions after the last ACK received.

To estimate the overall ETX, the values of e_b and e_d are combined using an EWMA filter to calculate the FB metric

$$\mathrm{FB}_n = \alpha \times \mathrm{FB}_{n-1} + (1-\alpha) \times e. \tag{2}$$

For each received probe packet, a new value of the FB metric is calculated replacing e by e_b in Equation 2. For w_d transmitted packets, the FB is calculated replacing e by e_d in Equation 2. Thus, the information of the two directions are considered, using both data packets and probe packets.

As in [6], in the simulations peformed for this research, the window size was 5. A history control factor $\alpha = 0.9$ was used for the filters.

C. F-LQE and Opt-FLQE

The F-LQE [10] is a receiver-initiated estimator based on fuzzy logic. Four different aspects of the link are used to obtain a holistic characterization, that is: packet delivery (SPRR), stability (SF), asymmetry (ASL), and channel quality (SNR).

The SPRR is the PRR filtered using an EWMA filter, with a window size of 5 and $\alpha = 0.6$. The SF is the coefficient of variation of PRR, that is calculated using a sliding window with the 30 most recent PRR values.

To assess the asymmetry of the link the PRR calculated in the neighbor nodes are used. The values of PRR in each node are transmitted together with the data packets. Then the ASL can be computed using $(\mathrm{ASL} = |p_u - p_d|)$. The p_u is computed every w received packets, and the p_d is obtained from a table that stores the most recent values of PRR transmitted by the neighbors. In the simulations $w = 5$ was used, and probe packets were used to calculate the values of p_u and p_d.

The metrics SPRR, SF and ASL capture important link characteristics, but they do not provide an accurate view of the channel quality, which can be obtained using hardware-based metrics. For example, a good link that has a relatively low SNR can be affected drastically by small changes in the topology of the environment. A link with high SNR is more resistant to those small changes.

To calculate the SNR, one value of RSSI is sampled from a received packet, and other value of RSSI is sampled after the packet reception, to obtain the noise floor. The SNR is then calculated subtracting these two values.

Finally, the four metrics are combined using fuzzy logic to compute the quality of link i as follows

$$\begin{aligned} \mu(i) = {} & \beta \mathrm{min}(\mu_{SPRR}(i), \mu_{SF}(i), \mu_{ASL}(i), \mu_{SNR}(i)) \\ & + (1-\beta)\mathrm{mean}(\mu_{SPRR}(i), \mu_{SF}(i), \mu_{ASL}(i), \mu_{SNR}(i)), \end{aligned} \tag{3}$$

in which $\mu_{SPRR}(i), \mu_{SF}(i), \mu_{ASL}(i)$, and $\mu_{SNR}(i)$ are the membership functions of each metric, which provide a value between $[0,1]$, that indicates the extent to which the link is considered having high delivery rate, high stability, low asymmetry, and high channel quality, respectively. As in [10], $\beta = 0.6$ was used. The membership functions were defined as:

$$\mu_{SPRR}(i) = \begin{cases} 0, & \text{if SPRR} \leq 0.25; \\ 1, & \text{if SPRR} \geq 0.95; \\ \frac{4\mathrm{SPRR}-1}{3}, & \text{otherwhise.} \end{cases} \quad \mu_{SNR}(i) = \begin{cases} 0, & \text{if SNR} \leq 1; \\ 1, & \text{if SNR} \geq 8; \\ \frac{\mathrm{SNR}-1}{7}, & \text{otherwhise.} \end{cases} \tag{4}$$

$$\mu_{SF}(i) = \begin{cases} 0, & \text{if SF} \geq 0.7; \\ \frac{-10\mathrm{SF}+7}{7}, & \text{otherwhise.} \end{cases} \quad \mu_{ASL}(i) = \begin{cases} 0, & \text{if ASL} \geq 0.5; \\ 1, & \text{if ASL} \leq 0.01; \\ \frac{-100\mathrm{ASL}+50}{49}, & \text{otherwhise.} \end{cases} \tag{5}$$

In the experiments described in [10], the F-LQE outperformed ETX and FB. The Opt-FLQE [7] is a modification of the F-LQE to improve the reactivity and reduce the computational complexity. It does not use the

SF, since it is necessary to iterate an array of 30 values to compute this metric, which is computationally complex for low-cost devices. To replace the SF, the Opt-FLQE uses a sender-side metric, the Smoothed RNP (SRNP), which assesses the required number of packet transmissions until a successful reception. In the simulations performed for this research a history control factor equal to 0.6 was used to calculate the SRNP. The values of SRNP calculated at the sender are transmitted together with the data packets to allow the receiver calculate the Opt-FLQE metric. The performance analysis described in [7] showed that Opt-FLQE is more reactive than F-LQE while still being more reliable for smart-grid environments

The other three metrics of Opt-LQE are calculated at the receiver and are based on PRR. With a sender-side metric, it is possible to capture the number of transmission attempts by the sender, and it is possible to have a good estimative of the LQ when only a few packets are received.

The membership function of SRNP is defined as

$$\mu_{SRNP}(i) = \begin{cases} 0, & \text{if SRNP} \geq 4; \\ 1, & \text{if SRNP} \leq 1; \\ \frac{4-\text{SRNP}}{3}, & \text{otherwhise.} \end{cases} \tag{6}$$

The final values of F-LQE and Opt-FLQE are the value of $\mu(i)$ normalized to fit between 0 and 100, and smoothed using an EWMA filter. In [7] $\alpha = 0.9$ was used for the EWMA filter, but for this paper $\alpha = 0.6$ was used, to obtain more reactivity.

Sometimes not all values used in both F-LQE and Opt-FLQE are available. In this case, the estimator calculates the LQ considering the membership functions of the available values (using at least SPRR and SNR).

III. EVALUATION METHODOLOGY

A. Simulation Model

The wireless channel can be modeled as stationary for a short term, despite the movements around the transmitter and the receiver. However, the properties of the channel can change significantly over time due to changes in the topology of the environment, which are not considered in the distributions used to model fading. This may require the recalculation of the distribution parameters, since these parameters may become obsolete over time [2][5].

To allow the simulation of LQEs for industrial WSN it is necessary to use a model that captures the channel characteristics for a long period of time. In a previous work [11], a simulation model based on a two-state Markov chain was developed, which captures the effects of fading, log-normal shadowing, and the non-stationary characteristics of the channel. In the current implementation, two instances of the model are used to model the wireless channel in the two directions of a link, to capture the asymmetry. In the model, abrupt changes in the channels characteristics can occur. The parameter p defines the probability that such changes occur. With p it is possible to simulate environments that remain unchanged for a long period of time and environments that present frequent changes in the topology. The simulation result obtained using the model is compatible with results from experiments performed in industrial environments [2] [5] [11].

B. Simulation setup

To evaluate the LQEs the Castalia simulator was used, integrated with the model described in Section III-A. Two nodes were used, a transmitter and a receiver, with acknowledgment and packet retransmission (with a maximum of four attempts). Both nodes transmit broadcast probe packets (called beacons) periodically, to be used by the LQEs. The simulation parameters are detailed in Table I.

TABLE I

PARAMETERS USED IN THE SIMULATION.

Distance between the nodes	20 and 35 meters
Physical and MAC layer	IEEE 802.15.4-CSMA/CA
Bit rate	250 $kbit/s$
Simulation Time	18000 s (5 hours)
Transmission power	0 dBm
Packet transmission rate	1 packet/s
Beacon transmission rate	0.2 packet/s
Transition probability (p)	0.1%

For the lognormal shadowing model the values of $n = 1.52$, $d_0 = 15$ m, $L(d_0) = 72.71$ dB, and $X_\sigma = 4.61$ dB were used. The noise floor was equal to -90 dBm. These values were obtained from experiments in an industrial environment described in [1]. More details about the implementation of the channel model can be found in [11].

The packet transmission rate used in the simulations (1 packet/s) is enough for many monitoring applications, such as temperature monitoring, and fault diagnosis in motors [13]. The beacon transmission rate is smaller, in order to reduce the overhead, and cause a smaller impact on the application.

As in the simulation one can obtain data from the operation of all nodes "simultaneously" from the trace generated by the simulator, it is possible to know the exact number of transmissions and receptions in a time period, which is virtually impossible considering only the data available in a specific node. Thus, it was possible to calculate the actual PRR in both directions during all the simulation, considering all transmitted and received packets (data packets, retransmitted data packets, ACKs, and beacons). Thus, a metric called Real PRR (RPRR) was used as a reference value to the metrics. The RPRR is calculated by the multiplication of the actual PRR of the two directions in a time period. The time period considered to calculate the values of RPRR was 10 seconds.

IV. RESULTS

All LQEs under evaluation present good accuracy to estimate the LQ when the link presents very good quality. Thus, the results focused in the analysis of the LQEs to estimate the quality of intermediate links, and during abrupt changes in the channel characteristics. In the charts the F-LQE and Opt-FLQE are plotted together, using RPRR as reference. The metrics ETX, and Four-Bit, are plotted together, using the value of $\frac{1}{\text{RPRR}}$ as reference. The results are shown for two scenarios: Scenario 1, with 20 meters of distance between the nodes, and Scenario 2, with 35 meters of distance.

A. *Results from Scenario 1*

In this scenario, the distance is relatively small, and the overral quality of the link was good. However, some variations can ocurr, and the LQEs need to be able to identify quickly the abrupt changes in the channel quality. The charts in Fig. 1(a) (F-LQE and Opt-FLQE) and Fig. 1(b) (ETX and Four-Bit) show the LQ in a period of 43 minutes, in which an abrupt change in the channel characteristics occurred, and the RPRR dropped approximately 15%, on average.

All the metrics identified the change in the LQ. However, Opt-LQE and Four-Bit started to react after about one minute, while F-LQE and ETX started to react only after seven minutes. The charts in Fig. 1(c) and Fig. 1(d) help to understand this behavior. After 54 minutes, an abrupt change in the channels characteristics ocurred, but only the up link (from transmitter to receiver) presented a drop in quality.

F-LQE and ETX are receiver-initiated estimators, and use the beacons to estimate the link quality. Thus, as the beacon transmission rate is relatively low (one beacon transmitted every five seconds), and considering the low PRR of the up link, these LQEs presented a larger delay to identify the change in the link quality. With a larger beacon transmission rate it is possible to make the metrics F-LQE and ETX more responsive, but it would consume more resources of the sensor nodes. The analysis of this trade-off is application-specific.

Four-Bit is a sender-initiated estimator, thus, it can rapidly identify the drop in the quality of the up link, since it uses the data packets to calculate the value of e_d. The Opt-FLQE is a receiver-initiated LQE, but uses a value calculated at the sender, the SRNP. As the values of SRNP are transmitted together with the data packets, which are transmitted with a rate five times larger than the beacons, the receiver obtains more quickly an updated value of SRNP, and can adjust the value of the metric.

The charts in Fig. 2(a) and Fig. 2(b) show the LQ in a period of 34 minutes, in which two abrupt changes in the channels characteristics occurred. The RPRR dropped approximately 5%, and then increased approximately 5%. In this case, all the metrics noticed the change in the LQ quickly. This can be explained with the analysis of the charts in Fig. 2(c) and Fig. 2(d). Since the changes in the channel characteristics, for both directions, occurred almost in the same way, and since the RPRR remained high (95% on average) during the drop in quality, all the estimators reacted prompty.

B. *Results from Scenario 2*

In this scenario, the distance was larger, and the overall quality was lower than in the Scenario 1. The charts in Figure 3(a) and Figure 3(b) show the LQ for a period of 33 minutes, in which one abrupt change in the channels characteristics occurred, and the RPRR dropped approximately 50%. Different from the results showed in Fig. 1, all the metrics noticed the change in the LQ prompty. This occurred because only the quality of the down link dropped significantly, and both the sender-initiated and the receiver-initiated metrics could identify the drop in the LQ quickly.

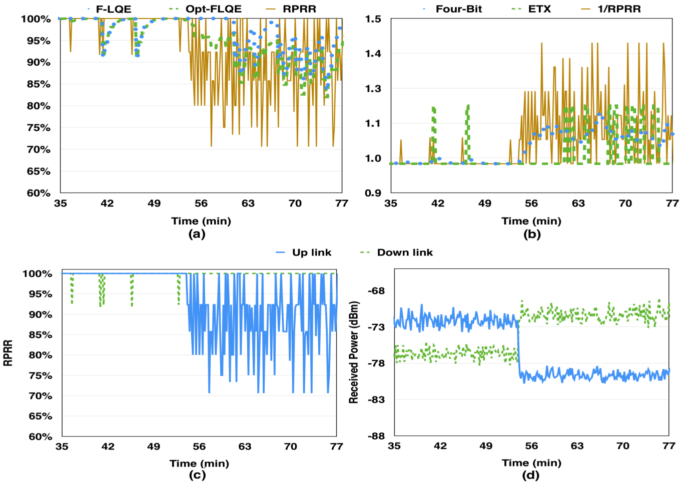

Fig. 1. Charts on the top - the LQ during 42 minutes for the Scenario 1. Charts on the bottom - RPRR and reception power during 42 minutes.

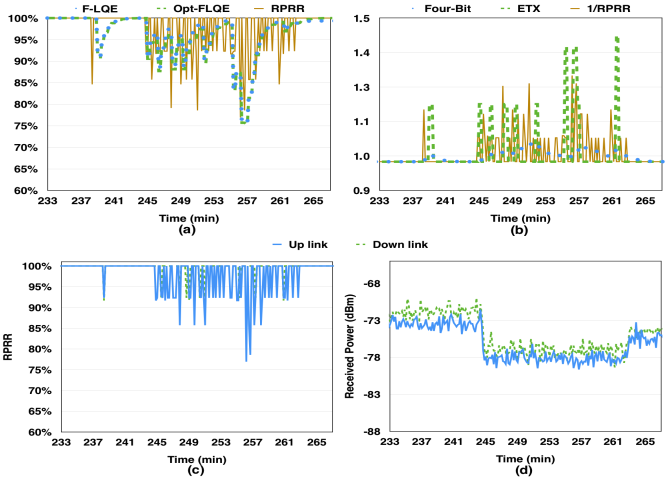

Fig. 2. Charts on the top - the LQ during 34 minutes for the Scenario 1. Charts on the bottom - RPRR and reception power during 34 minutes.

The charts in Fig. 4(a) and Fig. 4(b) show the LQ in a period of 35 minutes, in which one abrupt change in the channels characteristics occurred, and the RPRR dropped more than 80%. In this case, the down link presented a large drop in its quality, which led the RPRR to be close to 0, since the packets barely can be acknowledged in this scenario. Both F-LQE and Opt-FLQE reacted relatively fast, since the down link was the one that presented the drop of quality. However, they overestimated the LQ. This ocurred due to the very low quality of the down link. In this case, the ASL, that captures the asymmetry, could not be computed, since almost no beacons were received at the transmitter during this period. On the other hand, the high values of SPRR and SNR, calculated at the receiver, had a higher influence on the estimation. The Opt-FLQE presented a smaller value than the F-LQE, more close to the RPRR, due to the values of SRNP, that could be obtained from the sender.

In this scenario, the ETX presented good accuracy, but only reacted to the change after 10 minutes, since almost no probe packet is received at the transmitter due to the very low

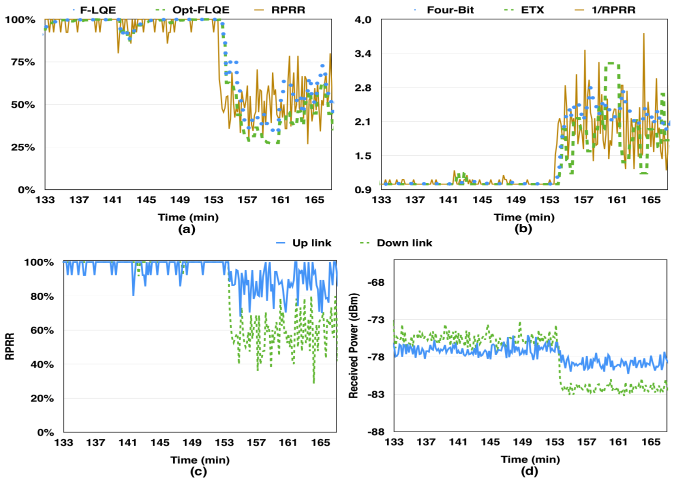

Fig. 3. Charts on the top - the LQ during 32 minutes for the Scenario 2. Charts on the bottom - RPRR and reception power during 33 minutes.

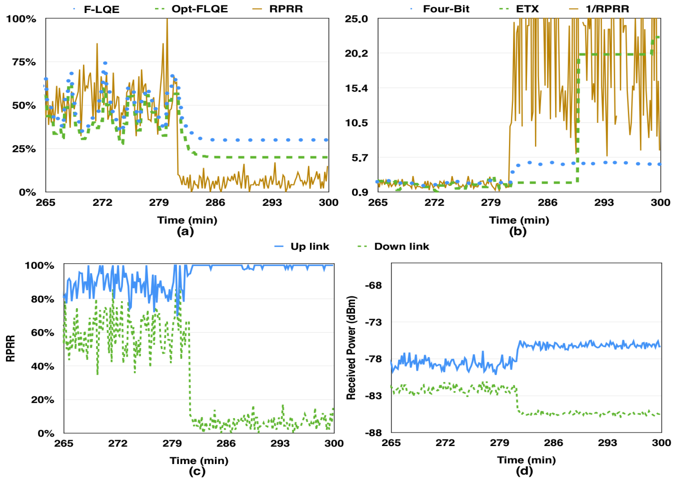

Fig. 4. Charts on the top - the LQ during 35 minutes for the Scenario 2. Charts on the bottom - RPRR and reception power during 35 minutes.

quality of the down link. The Four-Bit reacted quickly, but as the maximum number of transmission attempts is four, the maximum value of e_d is five, and during this period the e_b could not be calculated often, due to the low quality of the down link.

In general, all LQEs presented good accuracy in almost all scenarios, but Four-Bit, and Opt-FLQE presented a better reactivity to the abrupt changes in the LQ. The ETX presented low stability, which can impair the decision process of protocols that use the information provided by the estimator. The F-LQE and Opt-FLQE also presented low stability, in some cases, due to rapid variations in the channel quality. The Four-Bit presented the best stability, but can present low accuracy in some cases, as illustrated in Figure 4.

V. CONCLUSIONS

This paper presented an evaluation of some state-of-the-art LQEs for industrial WSN, using a realistic simulation model. Using this model, it was possible to observe the accuracy and the reactivity of these LQEs, considering the non-stationary behavior of the wireless channel in industrial environments, for different scenarios. Although some metrics presented good accuracy, and good reactivity, e.g. the Four-Bit and the Opt-FLQE, some challenges still remain. The reactivity can be optimized, since the most responsive estimators still takes about one minute to react in some scenarios, which can impair some applications. Besides, all LQEs use active estimation, and perform some processing at the transmitter (usually the end node in a WSN), thus the overhead on the network and on the end nodes can be high. As future work, optimization of the LQEs will be proposed, to reduce the overhead and improve the reactivity. Studies on the integration of LQEs with dynamic channel allocation mechanisms will be performed.

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